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What did the Southern Ocean look like 45 million years ago?

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Why do we care?

We can use past warm periods to understand the changes that might happen under current human-caused climate change. 45 million years ago, the Earth was $\sim 10^{\circ}\text{C}$ warmer than today (1, 2). The Southern Ocean has experienced rapid regional warming since the 1950s (3).

The Antarctic Circumpolar Current (ACC) is the world's longest current (4), transporting water between the Atlantic, Indian and Pacific Oceans. It's flow of the ACC causes mixing of nutrients within the water column supporting fish, whales and penguins.

45 Million years ago, we don't know if the ACC existed, which would have had major impacts on the Southern Ocean.

How do we look back in time?

Over time, sediment sinks to the seafloor and builds up in layers. To go back 45 myr ago, we have to find the right layer of sediment. Sediment from the sea-floor was drilled as sediment cores by the Joides Resolution as part of the Integrated Ocean Drilling Program. We have sampled these sediment cores from each of the sites on the map.

From the sediment, we pick out tiny fossils including fish teeth and foraminifera

Fish teeth are made of fluoro-apatite, which makes them really hard. After a fish has died, and the tooth has sunk to the seafloor, it captures the chemical signature of the water at the seafloor, before being buried.

From the fish teeth we measure how much Neodymium was in the waters. Neodymium is a rare-earth element, so we have to use really accurate instrument to measure it

Foraminifera are a type of marine phytoplankton. The shells of foraminifera are made of calcite. When they build their shell they capture the chemical signature of the water around them.

By measuring the amount of Oxygen and Carbon in the shells, we can reconstruct what the ocean conditions were.

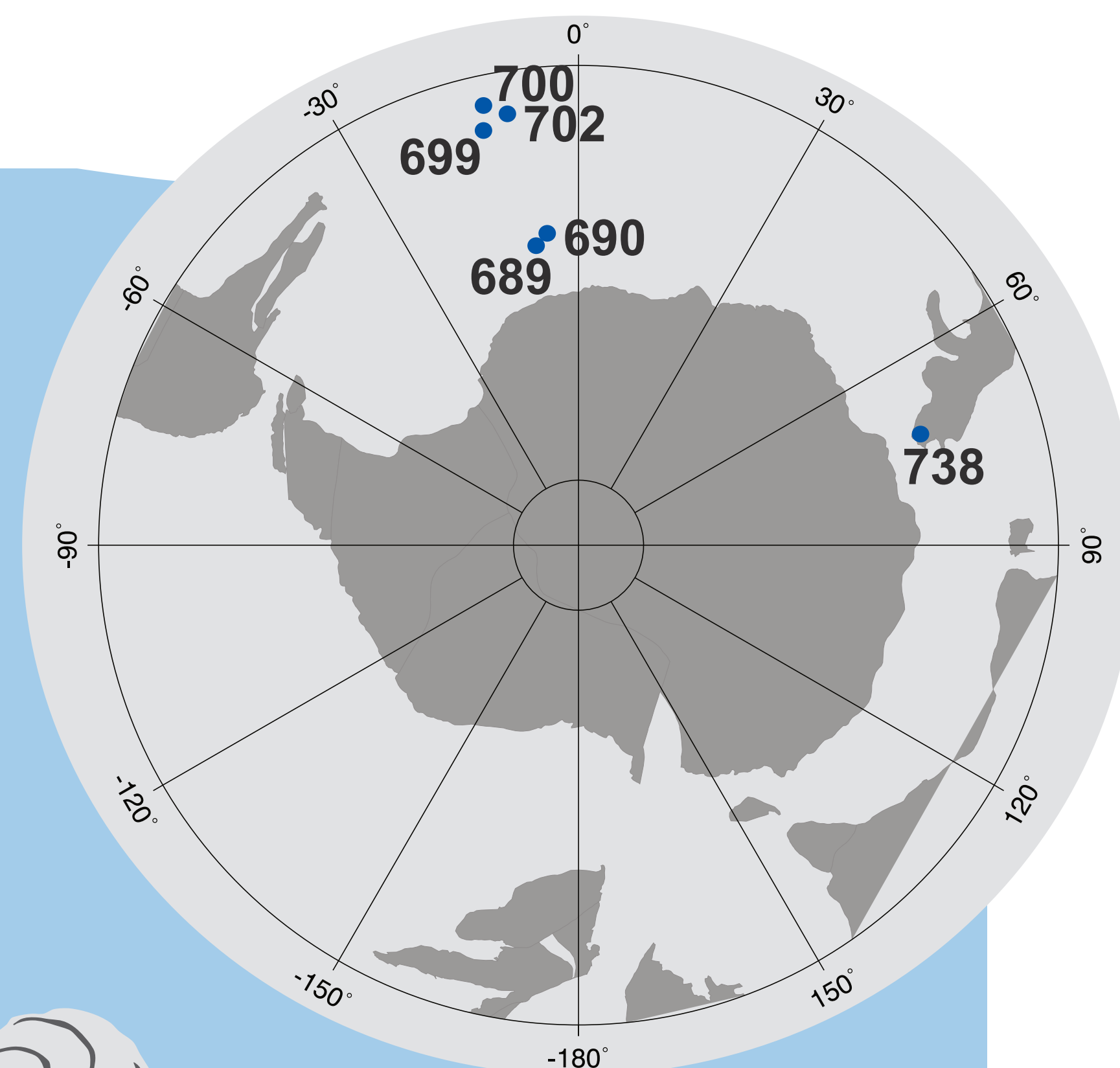
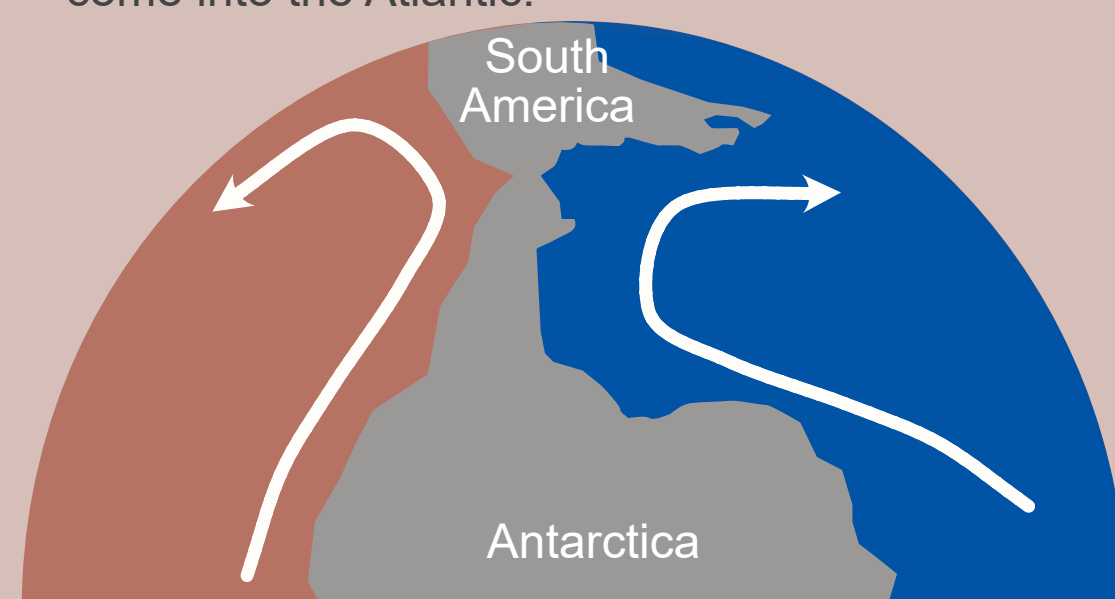


Plate tectonic reconstruction at 45 Myr ago from ODSN (9)

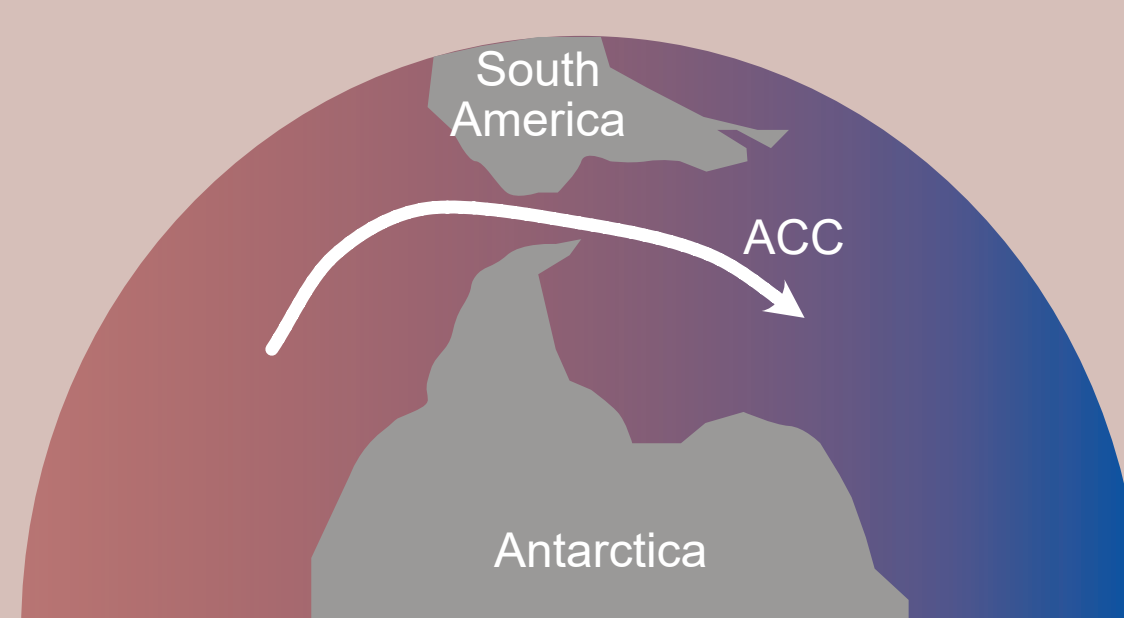
Using these sediments we answer questions on circulation, life and ocean mixing:

Was the Antarctic Circumpolar Current flowing 45 myr ago?

The Pacific and Atlantic Oceans have different types of Neodymium within them. Pacific neodymium is distinct from the Atlantic Ocean because of volcanic activity in the Pacific Ring of Fire. As such, it's easy to tell when Pacific waters come into the Atlantic.



We don't know if water could flow from the Pacific to Atlantic via Drake Passage 45 myr ago. To tell if Drake Passage was open, and the ACC was flowing through it, we look to see if there was Pacific Neodymium within the Atlantic. This is recorded within the fish teeth.



At the moment, we're still working on this question!

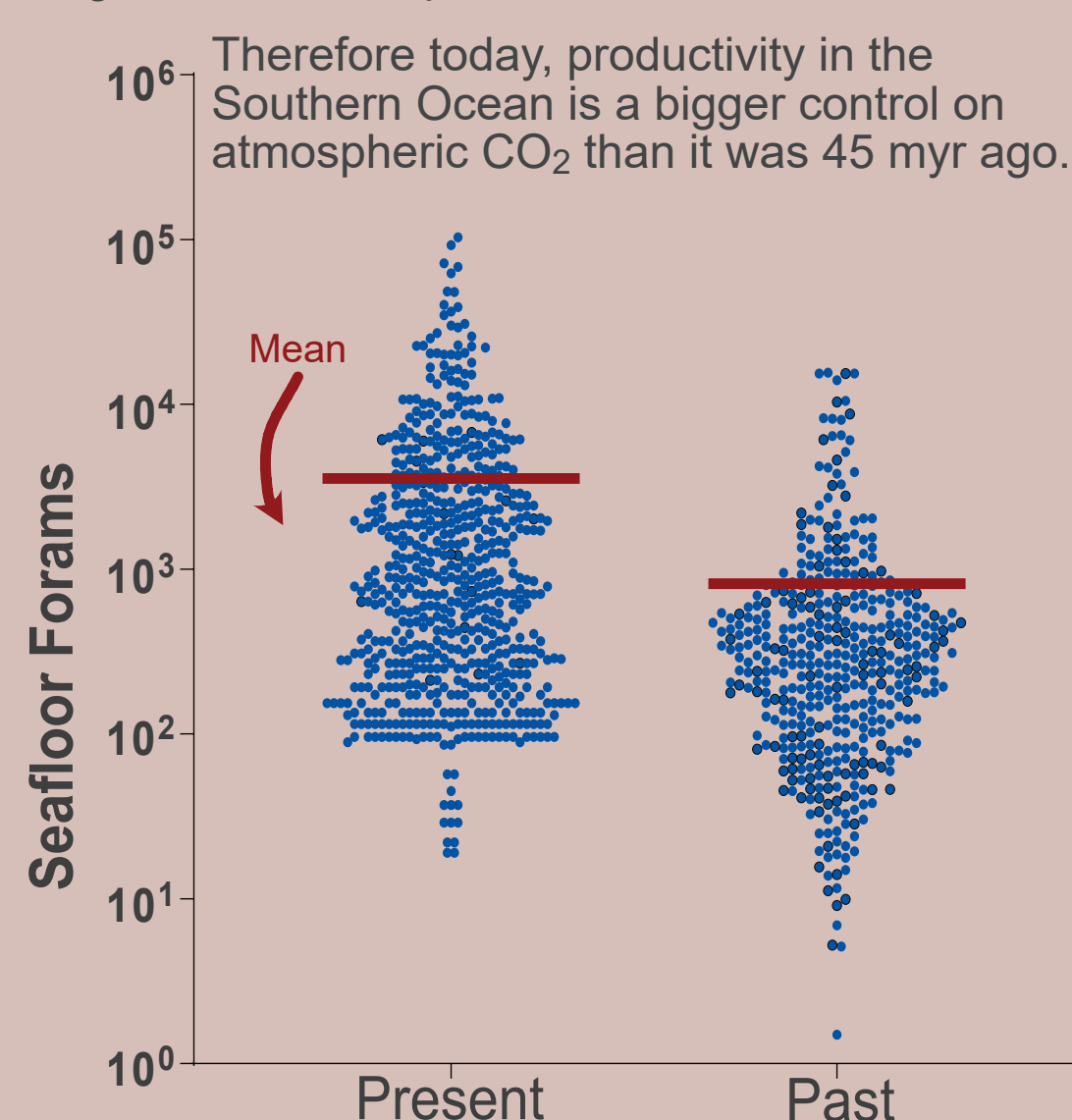
How does life in the Southern Ocean 45 myr ago compare to today?

We can work out how much life existed in the water column by looking at a plankton that lives on the sea floor. These seafloor dwelling foraminifera eat detritus that falls to the seafloor. Therefore, by counting the numbers of them, we can tell how much life lived in the water column above them.

From our work, we've concluded that there was on average less seafloor foraminifera 45 myr ago compared to today. This indicates that there was less life in the water column of the Southern Ocean compared to today.

This is important because phytoplankton living in the Southern Ocean water column today transform CO_2 into organic matter in a process known as carbon fixation(5,6). This means that this CO_2 is no longer in the atmosphere.

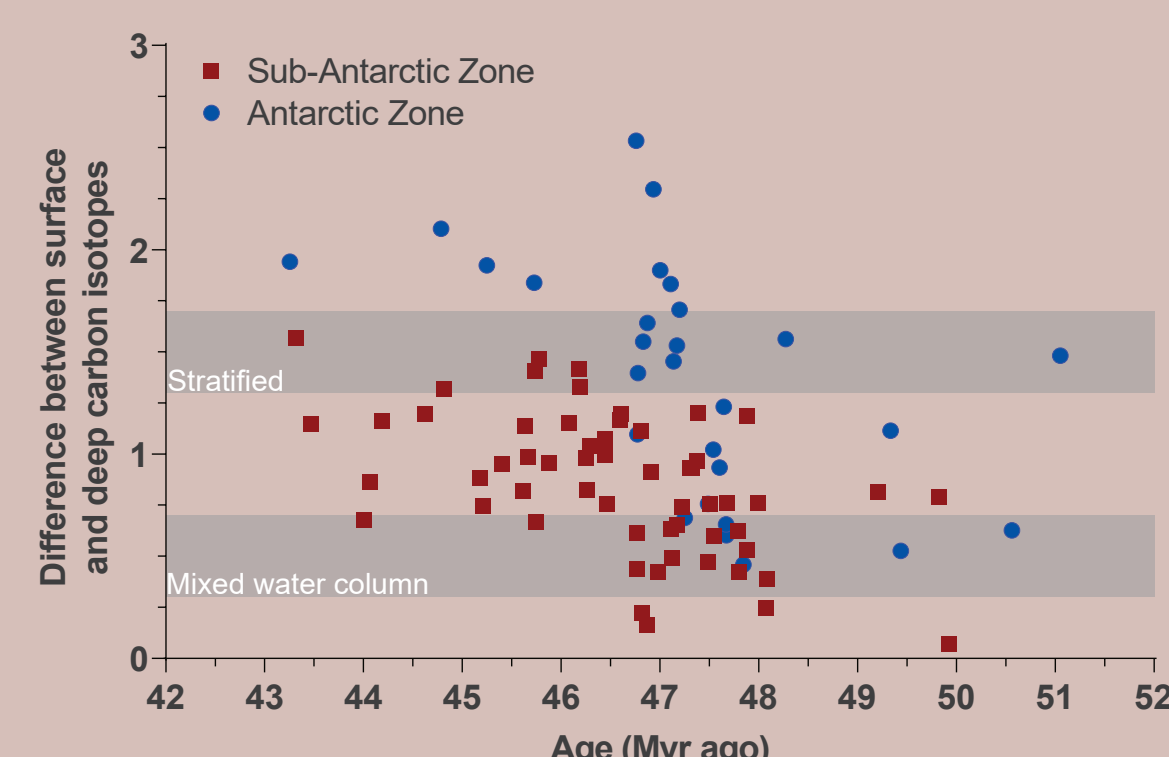
Therefore today, productivity in the Southern Ocean is a bigger control on atmospheric CO_2 than it was 45 myr ago.



How mixed was the Southern Ocean 45 myr ago?

Nutrients such as iron are key to carbon fixation (6-7). Without a mixing of the Southern Ocean, these nutrients remain stuck at depth (8) and aren't brought to the surface for photosynthesis.

By measuring the carbon isotopes in foraminifera shells we can work out whether the water column was being mixed. Vertical mixing redistributes nutrients stuck at depth, and therefore how much life could survive off them.



At 48 - 47 million years ago, there was a change in the mixing of the Southern Ocean. This affected both the Antarctic Zone ($>60^{\circ}\text{S}$) and the Sub-Antarctic Zone ($45-60^{\circ}\text{S}$).

At this point both regions become more stratified, implying a change in the wider circulation of the Southern Ocean, perhaps marking the inception of the ACC.

We expect that profiles of nutrients in the Southern Ocean will show a change at this same point - this is still a work in progress!

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